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Ultrafast Gain Dynamics in InAs–InGaAs Quantum-Dot Amplifiers

P. Borri, W. Langbein, J. M. Hvam, F. Heinrichsdorff, M.-H. Mao, and D. Bimberg

Abstract—The ultrafast dynamics of gain and refractive index in an electrically pumped InAs–InGaAs quantum-dot (QD) optical amplifier are measured at room temperature using differential transmission with femtosecond time resolution. Both absorption and gain regions are investigated. While the absorption bleaching recovery occurs on a picosecond time scale, the gain compression recovers with ~ 100 -fs time constant, making devices based on such dots promising for high-speed optical communications.

Index Terms—Amplifiers, modulators, quantum-dot lasers, ultrafast optics.

SEMICONDUCTOR quantum-dot (QD) lasers are attracting increasing interest due to their high material gain, low threshold current, and low chirp operation [1]. Recent developments in the fabrication of self-organized QD lasers emitting at room temperature (RT) on the QD ground-state transition [2] allow for first experimental tests of their performance. Some of the most important issues of QD lasers relates to their dynamic behavior, which is conjectured to be limited by the carrier capture into and relaxation in the QD's [1], [3]. Previous work dedicated to characterize directly carrier dynamics (capture, escape, lifetime) in self-organized QD's (see, for instance, [4], [5], and references therein) used mainly time-resolved photoluminescence experiments on unprocessed samples at low temperatures in the picosecond and nanosecond regime.

In this letter, we investigate for the first time the RT time constants of gain and refractive index dynamics in an electrically pumped InAs–InGaAs QD amplifier by femtosecond time-resolved differential transmission measurements. Both gain and absorption regimes are considered relevant for applications of QD's in laser amplifiers and electro-optical absorbers, respectively. The investigated sample is a p-i-n structure grown by MOCVD. Its active region consists of three stacked layers of binary/ternary InAs–InGaAs QD's separated by 21-nm-thick GaAs barriers placed in the center of a 120 nm GaAs layer. Two $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ cladding layers and a ridge structure of $8\text{ }\mu\text{m}$ width and $475\text{ }\mu\text{m}$ length provide optical confinement and waveguiding [2]. The end facets were tilted, avoiding back-reflection into the waveguide mode, thus

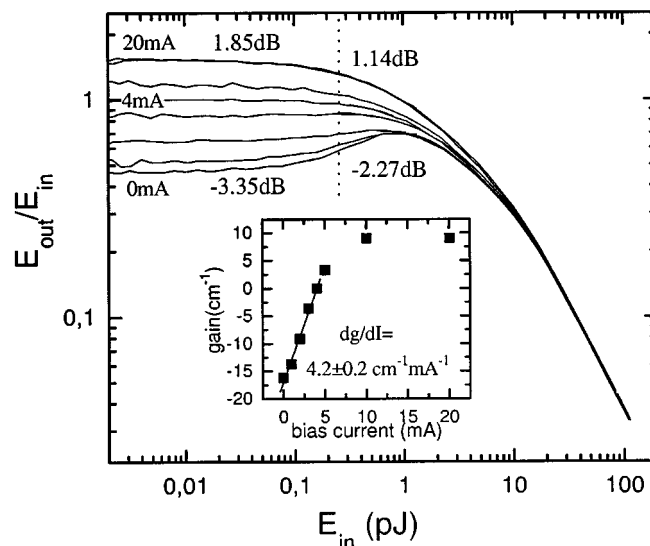


Fig. 1. Device gain measured from the transmission of a 150-fs optical pulse through the QD amplifier versus the input pulse energy for different bias currents, as indicated. The maximum gain and absorption values are indicated. In the inset, the corresponding modal gain and a linear fit to the modal gain versus current before saturation are shown.

inhibiting lasing. Photoluminescence measurements at RT show a ground-state dot transition at 1.148 eV ($1.08\text{ }\mu\text{m}$) with a broadening of about 60 meV and a wetting layer transition separated by 110 meV. Laser action at RT on the ground-state dot transition of this type of structure has been demonstrated [2]. The investigated structure shows RT lasing for a 1.5-mm cavity length at $1.057\text{-}\mu\text{m}$ wavelength, with a threshold current density [6] of 417 A/cm^2 . Note that the density of states deduced from the photoluminescence spectrum corrected by a Boltzmann population factor at RT results in a dot ground-state maximum at $1.06\text{ }\mu\text{m}$. We performed both single-pulse transmission and pump-probe experiments, using optical pulses from the idler of an optical parametric amplifier, providing Fourier-limited 150-fs pulses centered at $1.08\text{-}\mu\text{m}$ wavelength with 13 nm (14 meV) spectral width at a 300-kHz repetition rate. The light was coupled into and out of the device by aspheric lenses with high numerical aperture. The transmission of single pulses through the device was measured by a cooled Ge-detector and lock-in technique. The pump-probe experiment was performed using a recently proposed novel version of a heterodyne detection scheme that allowed us to use copolarized (in the TE mode) and co-propagating pump and probe beams with a low repetition rate laser system [7].

The transmission (ratio between the pulse energies at the output and at the input of the device) versus the input pulse

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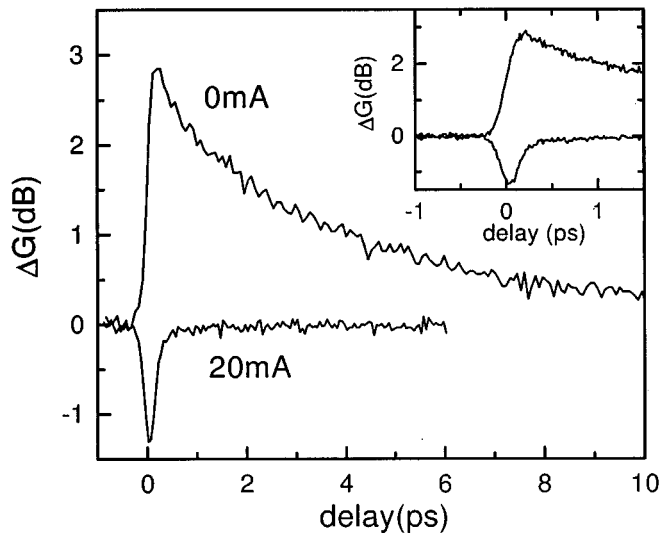


Fig. 2. Pump-induced gain change measured in a heterodyne pump-probe experiment at maximum gain (20 mA) and absorption (0 mA) in the device. In the inset, a zoom of the dynamics up to 1.5 ps.

energy is shown in Fig. 1 for different bias currents. The transmission is corrected from coupling, waveguide, and reflection losses. For small input energies, an absorption of -3.35 dB is found at zero bias, transparency occurs at 4 mA, and a maximum gain of 1.85 dB is reached at 10 mA. From the corresponding modal gain g (see inset of Fig. 1), a differential gain of $4.2 \text{ cm}^{-1}\text{mA}^{-1}$ before saturation is deduced. With increasing input energy, a bleaching of the absorption and a depletion of the gain occurs due to stimulated transitions induced by the pulse. For high input energies (>1 pJ), an additional reduction of the transmission due to two-photon absorption (TPA) is present at all bias currents. Amplified spontaneous emission spectra indicate a strong filling of the ground-state dot transition above 10 mA and the occupation of higher excited states, which is in agreement with the saturation of the gain.

For a pump input energy of 0.27 pJ, the induced change in the probe transmission, resonant to the dot ground-state, has been investigated for different bias currents. Note that this pump energy is in the small signal regime, with minor contribution of TPA (see dotted line in Fig. 1 and the indicated values). In Fig. 2, the gain change in decibels deduced from the probe transmission change is shown at 0 and 20 mA as a function of the pump-probe delay. A striking difference between the absorption and the gain recovery dynamic appears. At 0 mA, pump-induced absorption bleaching occurs, which reaches a maximum value of 2.8 dB and then recovers over several picoseconds. At 20 mA bias, a gain compression up to -1.3 dB that recovers in less than 0.3 ps is observed. The data show that the pump-induced spectral-hole burning (SHB) in the absorption case builds up with the time integral of the pulse, according to a recovery time much longer than the pulse duration, whereas in the gain case, it recovers on a time that is either comparable to or shorter than pulse duration. In the inset, a zoom of the dynamics over the first 1.5 ps is shown. It can be clearly seen that the maximum absorption bleaching occurs after the pump pulse, whereas the gain compression nearly follows the pulse intensity autocorrelation. This

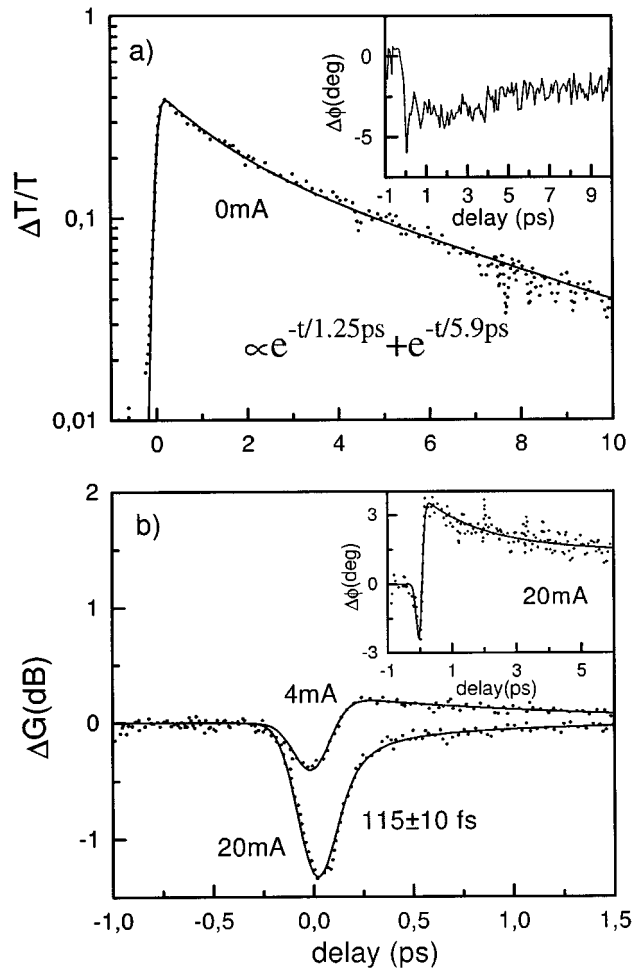


Fig. 3. (a) Differential probe transmission change in absorption versus delay time. The solid line is a bi-exponential fit to the data proportional to the indicated formula. The inset shows the corresponding phase change. (b) Pump-induced gain change close to transparency (4 mA) and at maximum gain (20 mA). In the inset the phase dynamic at 20 mA. Solid lines are fit to the data.

is also reflected in the higher maximum absorption bleaching compared with the gain compression.

We interpret these dynamics in the following physical picture. In the absorption case, the dots are initially empty. When the pump arrives, bound electron-hole pairs (excitons) are created in the dot ground state, leading to a bleaching of the absorption. This recovers by spontaneous carrier recombination or by carrier escape from the dot ground state. Typical spontaneous lifetimes in QD's are of several hundreds of picoseconds, as measured by time-resolved photoluminescence [5] (much longer than the measured absorption bleaching recovery), which should be then attributed to carrier escape by phonon absorption. In the top part of Fig. 3, a fit to the data is shown by convoluting the pulse intensity autocorrelation with a response function [8]. We obtain a good fit using a bi-exponential response function with two equally weighted time constants of 1.25 and 5.9 ps. They can be attributed to hole and electron escape times since the absorption bleaching is proportional to the sum of electron and hole occupation numbers [9]. The escape, which represents a heating of the optically excited excitons, also appears in the phase dynamics

(see inset of Fig. 3) as a heating process [8]. The lack of a long-lived population in the differential transmission, which we would expect once the thermal equilibrium is reached, is due to the diode structure of the sample. Once the carriers have escaped from the ground state, the built-in electric field of the diode at zero bias removes them out of the active region. When a flat band configuration is realized by a small applied bias current, long-lived population effects are observed. In the gain case, the dots are initially occupied, and, by stimulated emission, the pump leads to a reduction of the exciton population (gain compression) that recovers by relaxation of carriers into the dot ground state. The measured recovery time is, therefore, a direct measure of the carrier relaxation time from excited states into the dot-ground state in a QD amplifier *under working conditions*. Note that the used bias current of 20 mA corresponds to a maximum modal gain that is just enough for ground state lasing of the investigated structure, and it is not an unrealistic working point for QD lasers. In the bottom of Fig. 3, a fit to the gain data is shown. We should comment that even though the pump input energy was far from a strong TPA, a small contribution in the measured gain compression is still due to TPA of the probe and pump pulses, resulting in a reduced probe transmission that follows the intensity autocorrelation [8]. Since the TPA is bias independent (i.e., mainly not in the active region), according to Fig. 1, we can estimate this contribution by comparison with the differential transmission at the transparency current, where the net stimulated transition rate is zero, and only the TPA effect should appear. In addition, in the bottom of Fig. 3, the data at 4 mA are shown together with their fit, from which we deduce a TPA at zero delay of -0.5 dB when taking into account the small absorption bleaching still present. This estimate is consistent with measurements at high input power where the TPA dominates the response. The fit at 20 mA is then performed by fixing the amplitude of the TPA contribution and by including the so-called coherent artefact as half of the signal at zero pump-probe delay [8]. The amplitude of the SHB effect is given by comparison with the maximum absorption bleaching that give the strength of the stimulated transitions induced by the pump. The only free parameter is the SHB recovery time constant, and we obtain from the best fit 115 ± 10 fs, which is slightly shorter than the pulse duration. Note that the fit procedure convolutes the pulse intensity autocorrelation with the response function that *can* have a time constant shorter than the pulse duration, resulting in a small shift and a slight asymmetry toward positive delay, as observed. The measured ultrafast SHB recovery in the gain case thus indicates ultrafast carrier relaxation in electrically pumped QD amplifiers, which is very promising for high-speed applications. The carrier relaxation occurs probably via Auger scattering from the excited states, partly occupied at 20 mA, into the dot ground state, as recently theoretically proposed [10] and experimentally shown in [9] and [11]. Note that the occurrence of such ultrafast scattering processes imply fast dephasing times, i.e., large homogeneous broadening (10–20 meV), which we have confirmed by four-wave mixing experiments [12], and which influence the laser performance at RT [13].

We should comment that the fit of the gain data at large delay (up to 6 ps) also shows a minor contribution with slower exponential decay of 0.7 ± 0.1 ps time constant, which is possibly due to carrier heating [8] (CH). Such CH effect also appears in the phase dynamic (see inset) but with a recovery time of 2 ± 0.5 ps. The interpretation of this behavior is beyond the scope of this letter and up to future investigations.

In conclusion, we have measured the recovery time constants of gain dynamics in an electrically pumped QD amplifier. While the absorption bleaching recovers bi-exponentially over few picoseconds due to carrier escape from the dot ground-state, the gain compression recovers in only ~ 100 fs, due to carrier relaxation into the dot ground state, making devices based on such QD structures very promising for high-speed optical communications.

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